Study on the Dynamics during Longitudinal Compression of Intense Charged Particle Beams with Compact Simulator

Yasuo Sakai, Mitsuo Nakajima, Jun Hasegawa,
Takashi Kikuchi [a] and Kazuhiko Horioka

Departmet of Energy Sciences,
Tokyo Institutes of Technology
[a] *Department of Electrical Engineering,*
Nagaoka University of Technology

Back Ground

-Heavy ion beams are expected to be a potential driver for high energy science.

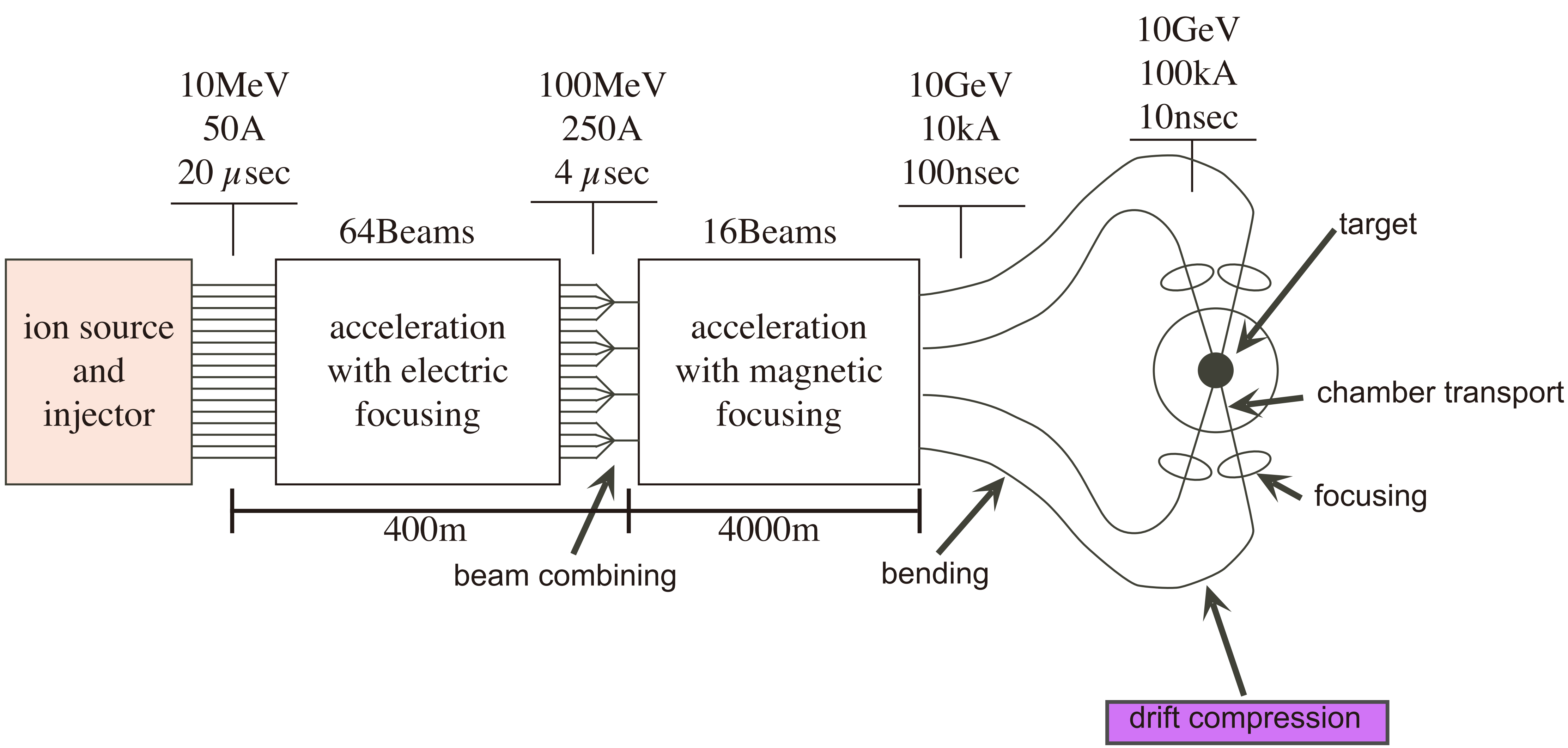
-We need to increase the beam power more than TW level in case of heavy ion fusion.

➡ Longitudinal bunch compression is crucial.

However, unpredictable energy dissipation and the emittance dilution may occur with rapid manipulation of intense beams.

Rapid Longitudinal Compression is Crucial

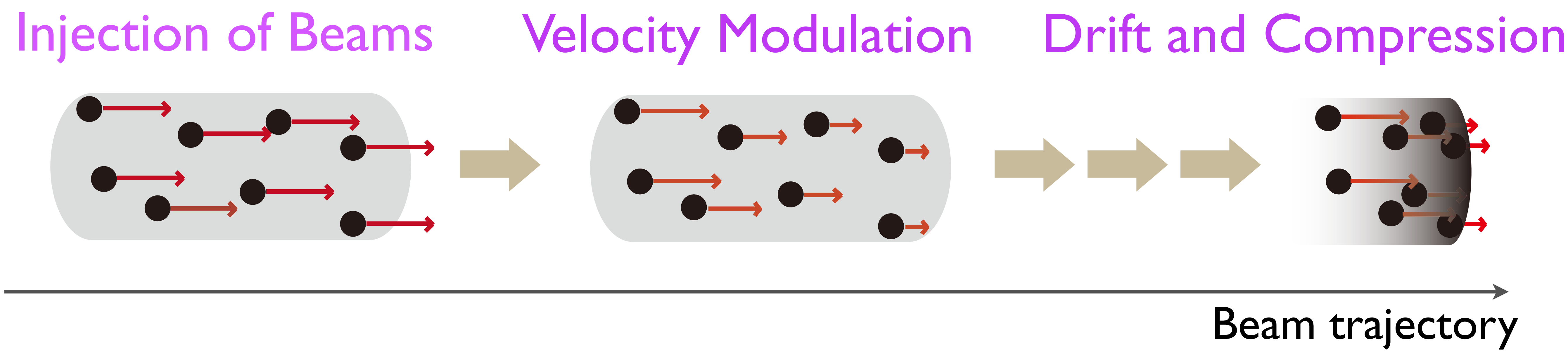
-Intense and high-power beams are transported. At the final stage of acceleration, beams are longitudinally compressed.

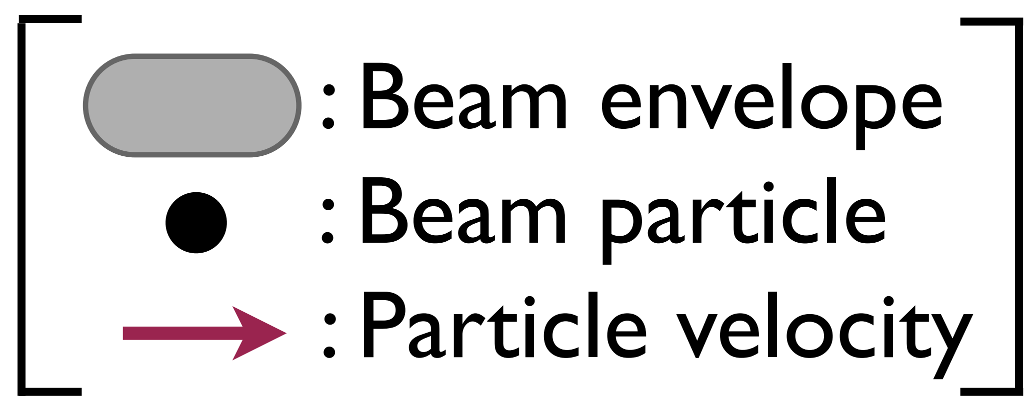


Concept of heavy ion fusion driver

(Ref : Bangerter,R.O, *Fusion Eng. Des. 44(1998) 71*)

Longitudinal Bunching is achieved with drift compression





1. Beam Injection
2. Apply modulation voltage
3. Transport the beam to the focus point
4. Compression is completed

Rear particles catch up front particles through the transport line.

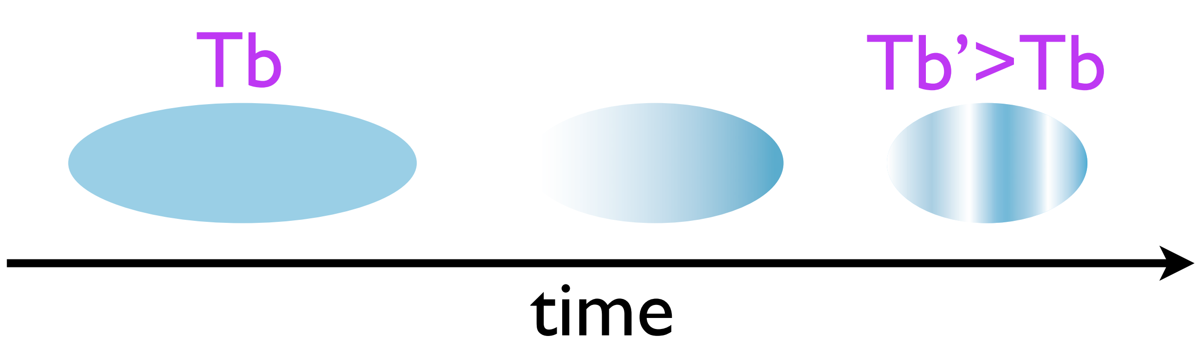
Emittance Evolution Disturbs Longitudinal Compression at Final Bunching

-Compression ratio depends on

1. Modulation accuracy
2. Initial beam emittance
3. Quasi-static space-charge effects
4. Collective effects (Dynamical Space-Charge effects)

-Collective effects may induce unpredictable energy dissipation and emittance dilution.

-Non-stationary beam density disturbance may induce the non-neutral plasma wave with rapid modulation.



Purpose and Experimental Scheme

-To investigate the collective effects on emittance evolution and beam dynamics during bunching are our primary concern.

Problem

The evolution of emittance during the longitudinal bunching should be discussed in 6-dimensional phase space.

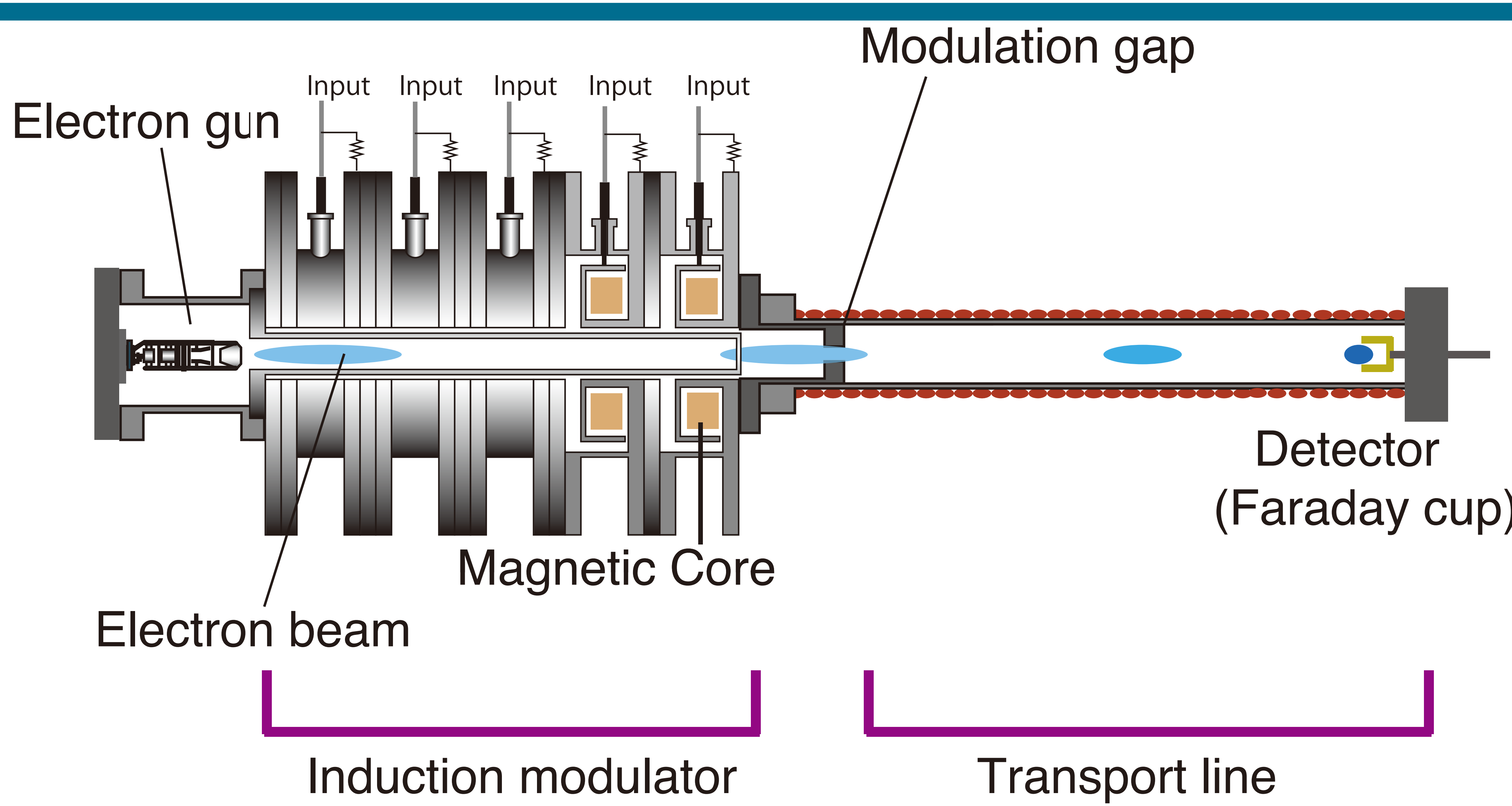
→

Our approach

Beam bunching through longitudinal magnetic fields ;
The transverse motion is suppressed and the emittance evolution is reflected to the compression ratio.

-Parametric study with a compact simulator should lead us deep understanding of bunching dynamics.

Experimental Configuration



-An electron beam is injected to the modulation gap and applied modulation voltage.

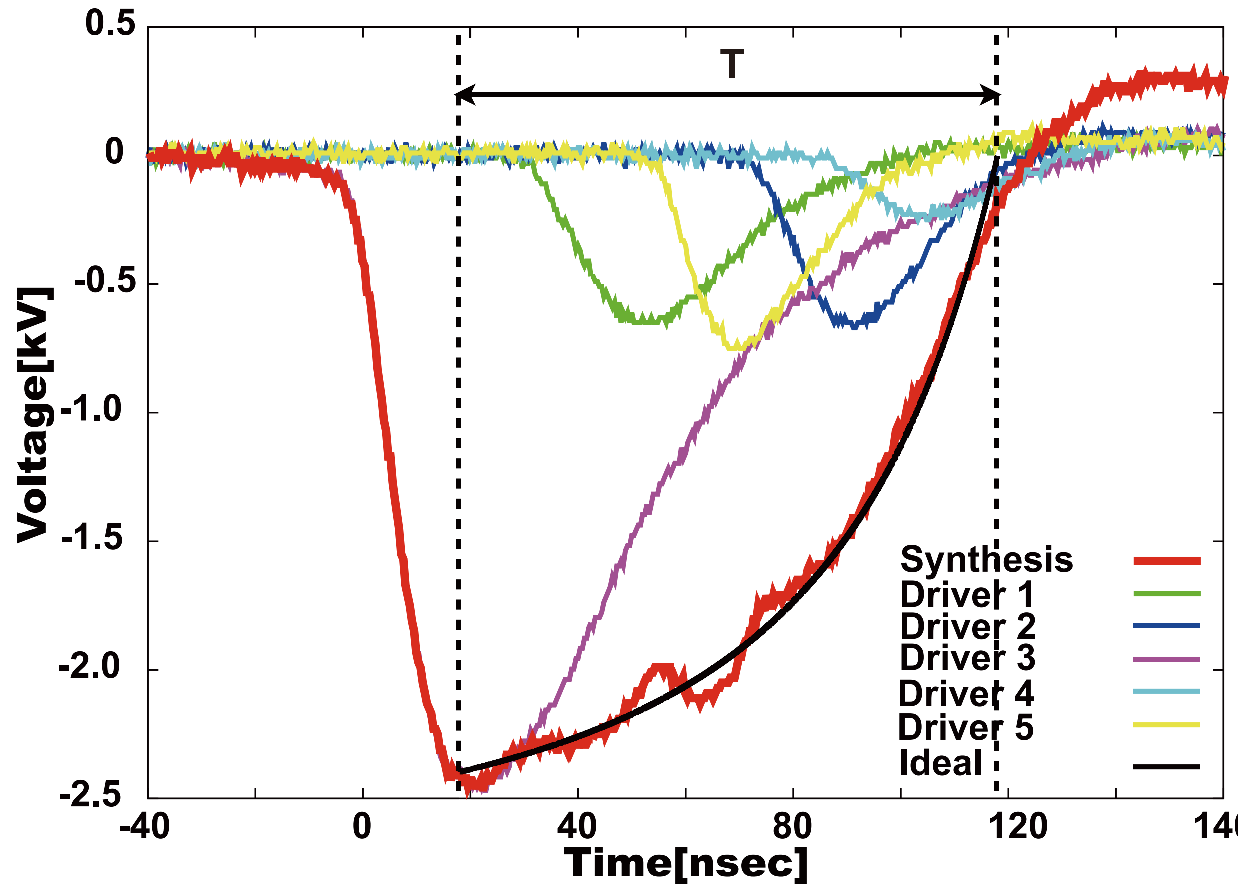
-Modulation voltage is synthesized with an induction adder composed of 5 units.

Modulation Voltage Waveform

-Derived modulation voltage for longitudinal compression.

$$V_{dec}(t) = \frac{m_e}{2q_e} \frac{1}{(\sqrt{\frac{m_e}{2q_e V_o}} + \frac{T-t}{L\mathrm{f}})^2} - V_o$$

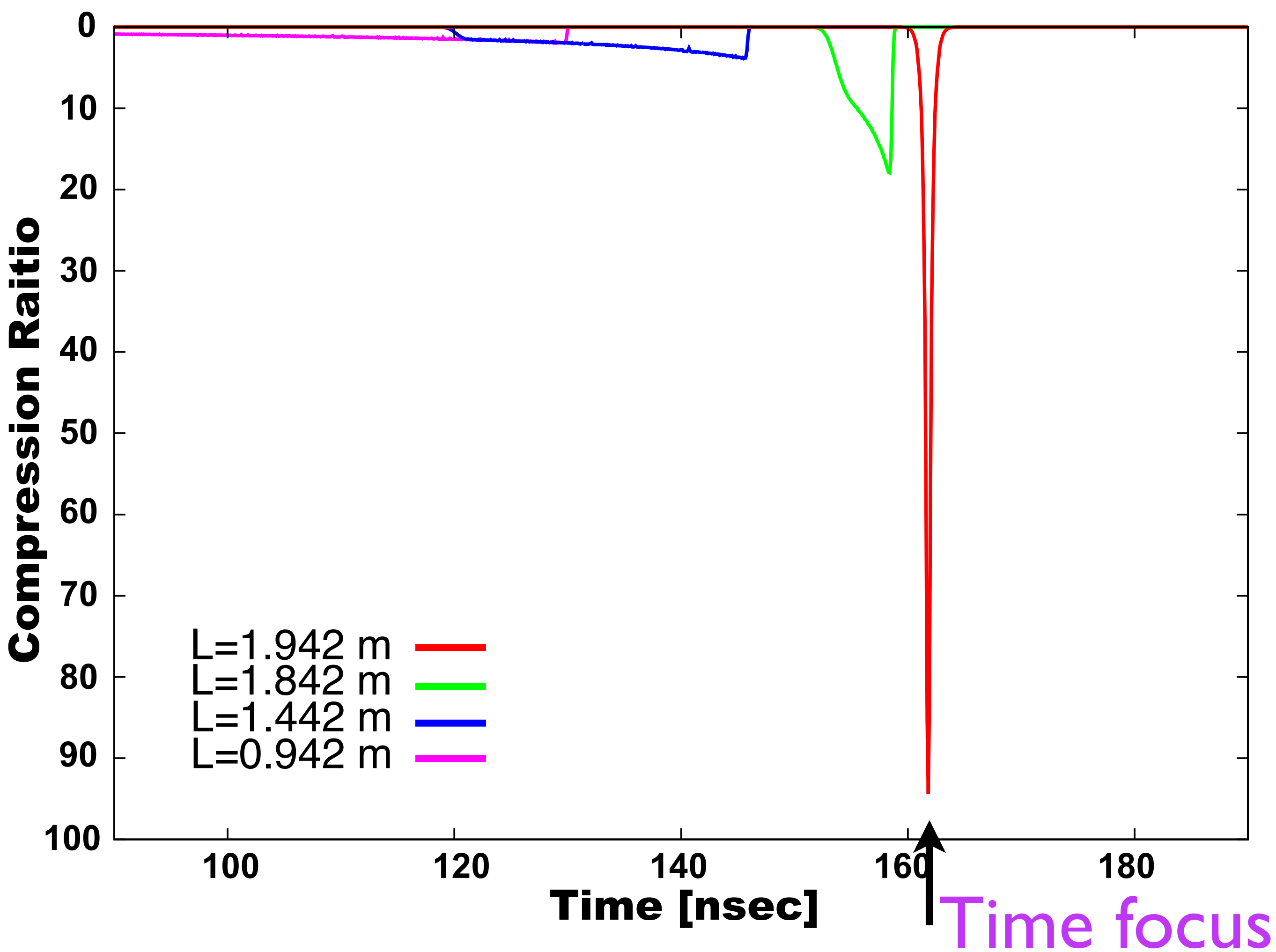
Lf : Focal distance
Vo : Extraction voltage
T : Modulation time length



Beam bunch converges to one point at focal distance with no space-charge and no energy dispersion.

-The modulation waveform synthesized with induction adder : Red line
-Ideal waveform: Black line
(Lf = 1.942 m ,Vo =2.8kV ,T = 100 ns)

Estimation of the Bunching Process



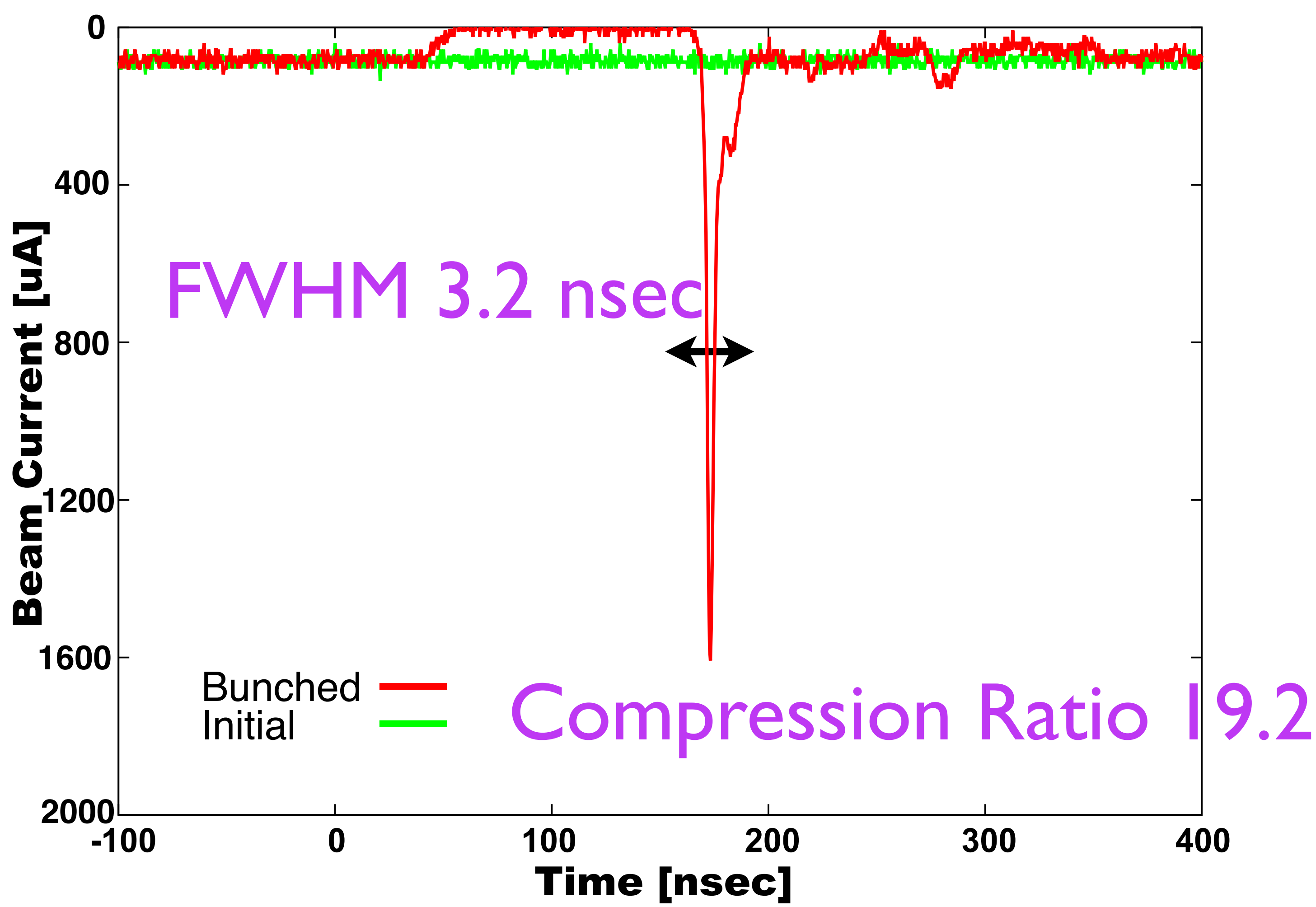
-Particle tracking code calculation results with ideal modulation voltage (Lf=1.942m) and finite temperature (0.017eV).

No space-charge.

-Injected Beam bunch gradually is compressed according to the velocity tilt, and as beam bunch approaches to the focal point, the compression ratio abruptly increases.

Typical Waveform of Bunched Beam Current

- Continuous beam is longitudinally compressed. The average initial beam current is estimated to be 84 uA (green line) and the bunched peak current increased 1610 uA (red line) .



- Compression ratio (CR) is defined as [Peak current] / [Initial beam current]

Criterion of Space-charge Dominated Region

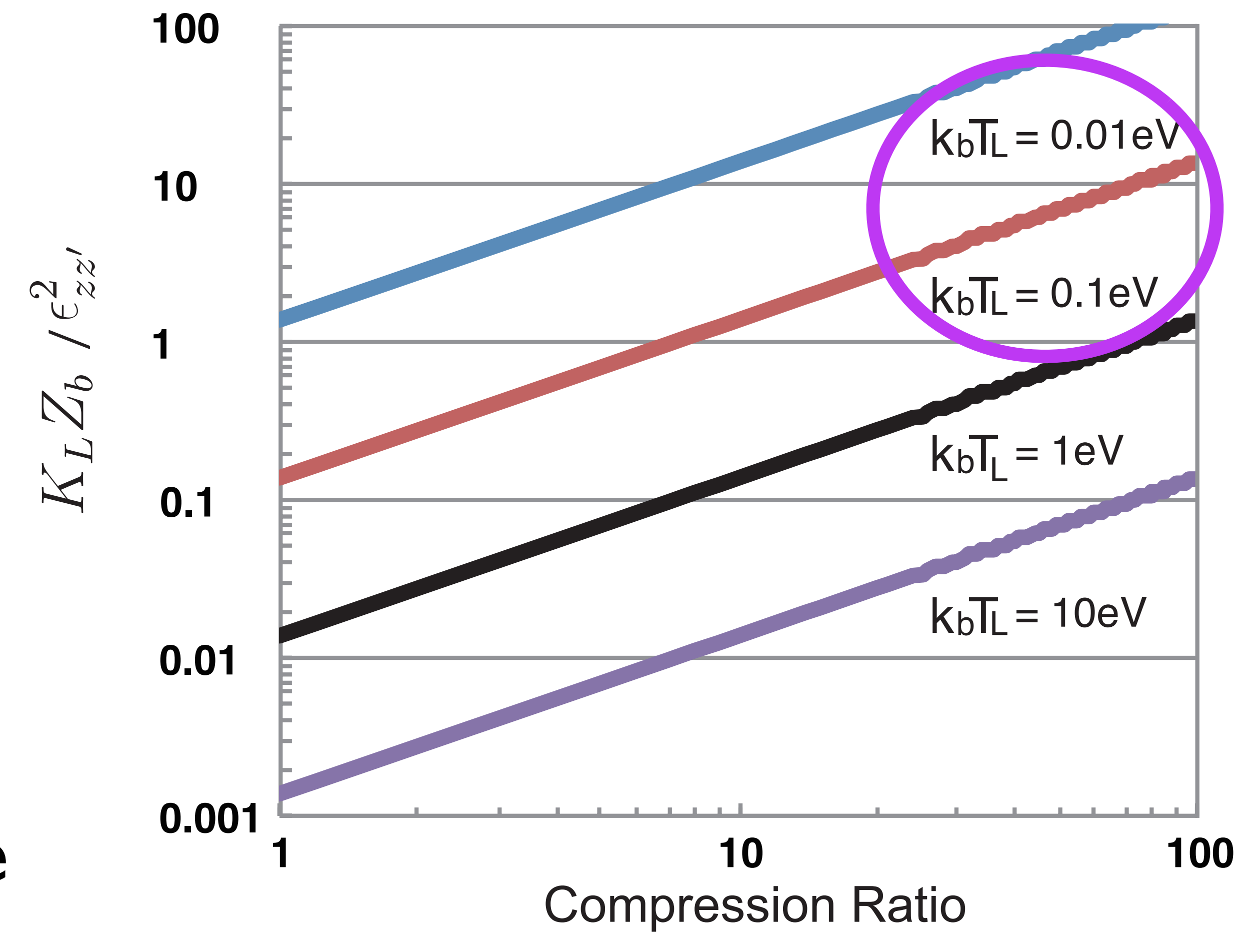
-Analytical estimation with 1D beam envelope equation

$$\frac{d^2 z_m}{ds^2} + k_z z_m - \frac{K_L}{z_m^2} - \frac{\epsilon_{zz'}^2}{z_m^3} = 0$$

$$\Rightarrow \frac{K_L Z_b}{\epsilon_{zz'}^2} = \frac{3egI_{bo}\tau_{bo}}{40\pi\epsilon_0 z_b\ k_b T_L} > 1$$

τ_o : initial beam pulse length
T_L: Longitudinal beam temperature
$2Z_b$: Bunch length of compressed beam

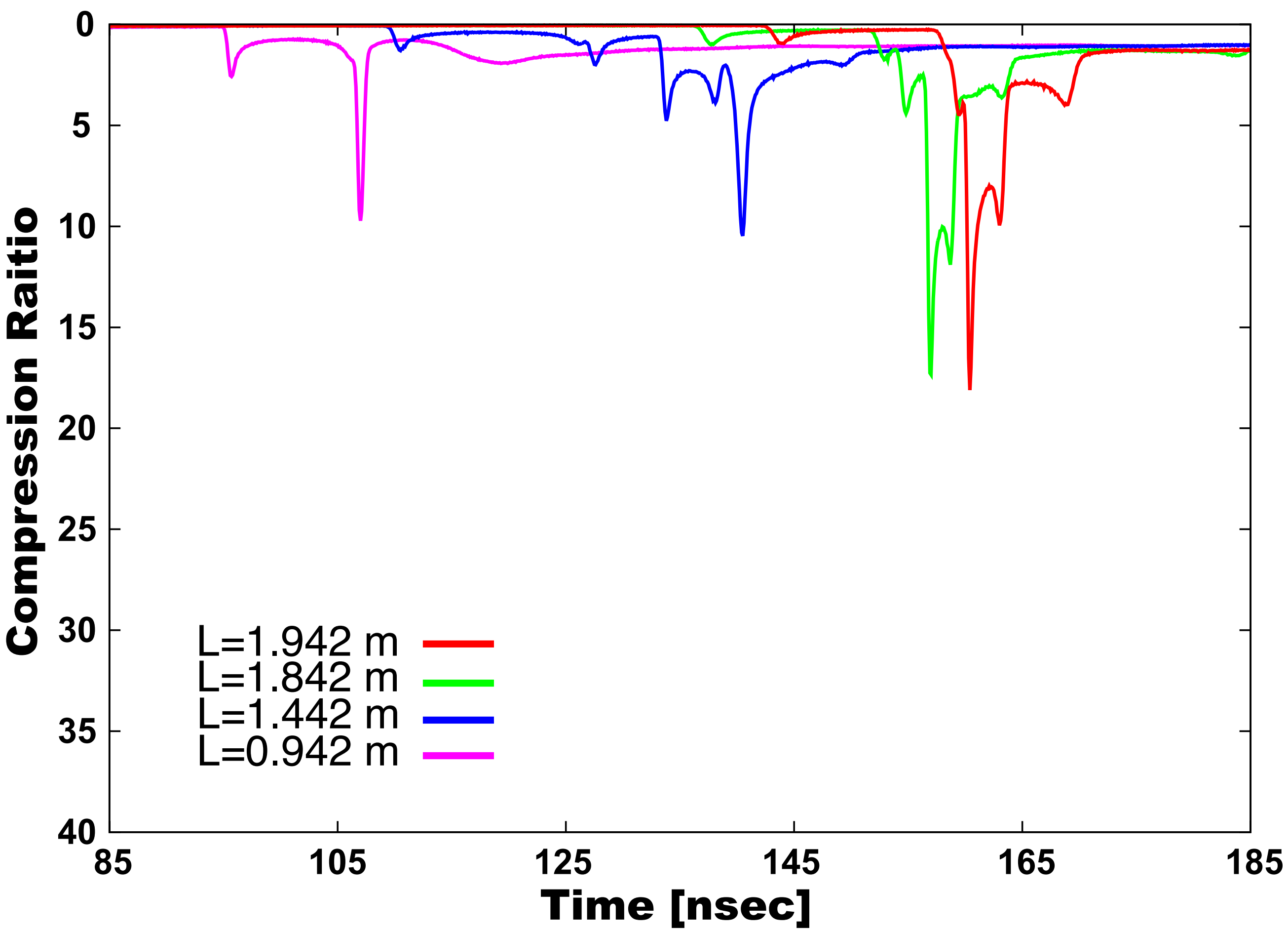
Our beam temperature around here



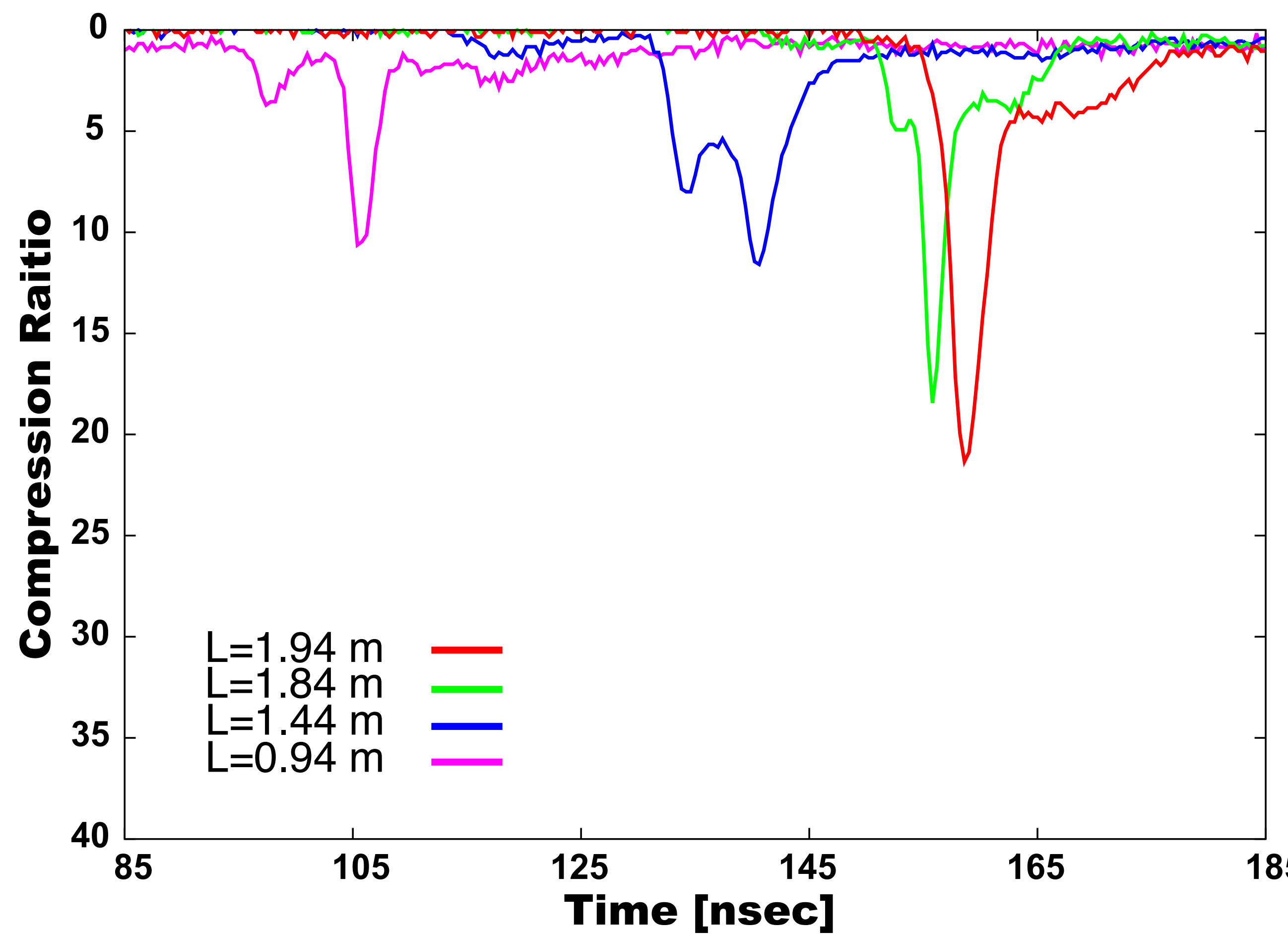
-With initial beam current 80 uA and pulse length 100 nsec

-Space-charge becomes dominant in beam dynamics as bunching proceeds

Evolution of the Bunching Process



Simulation

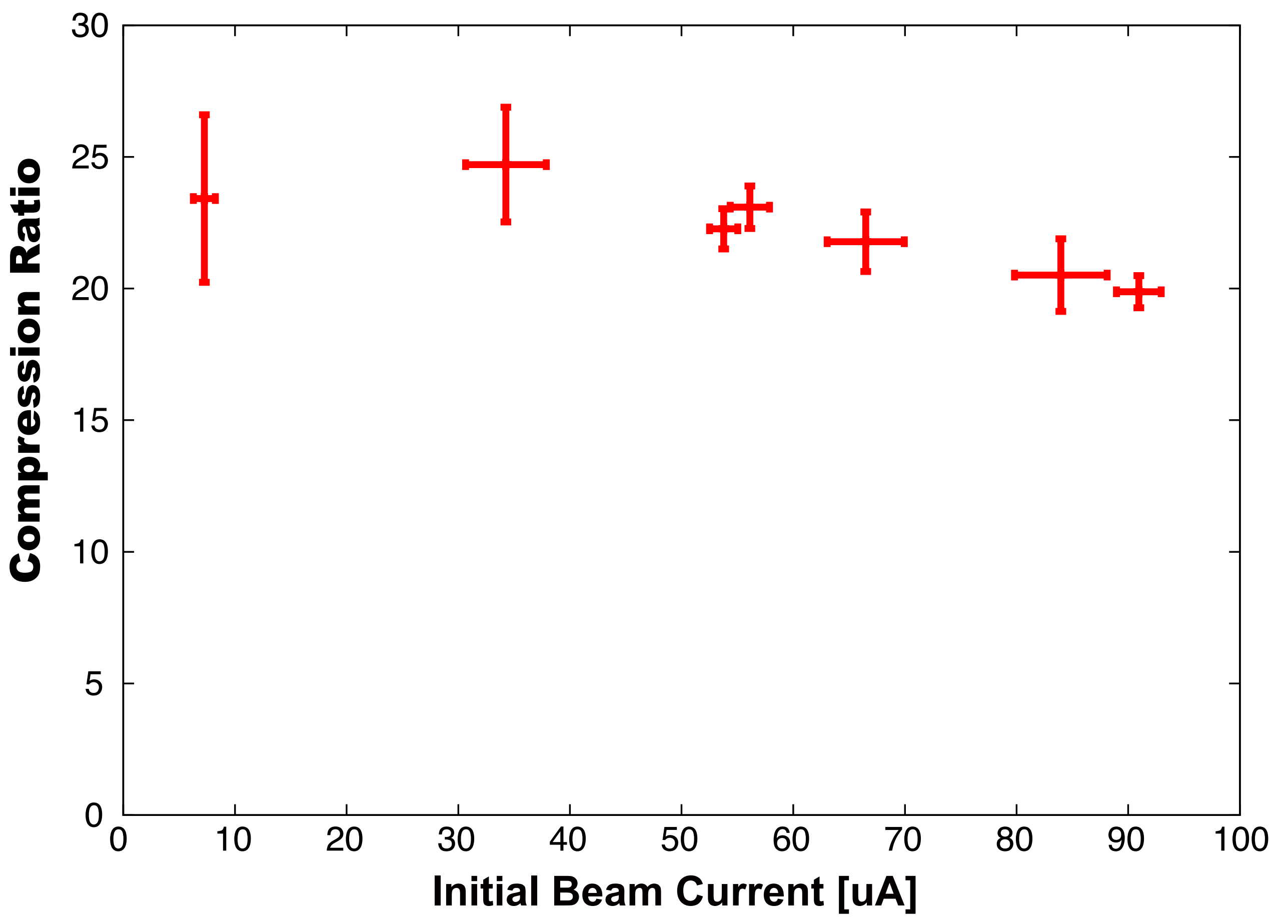


Experimental

-As the beam bunch approached to the focal point,
the bunched beam seemed to be broaden in experiment

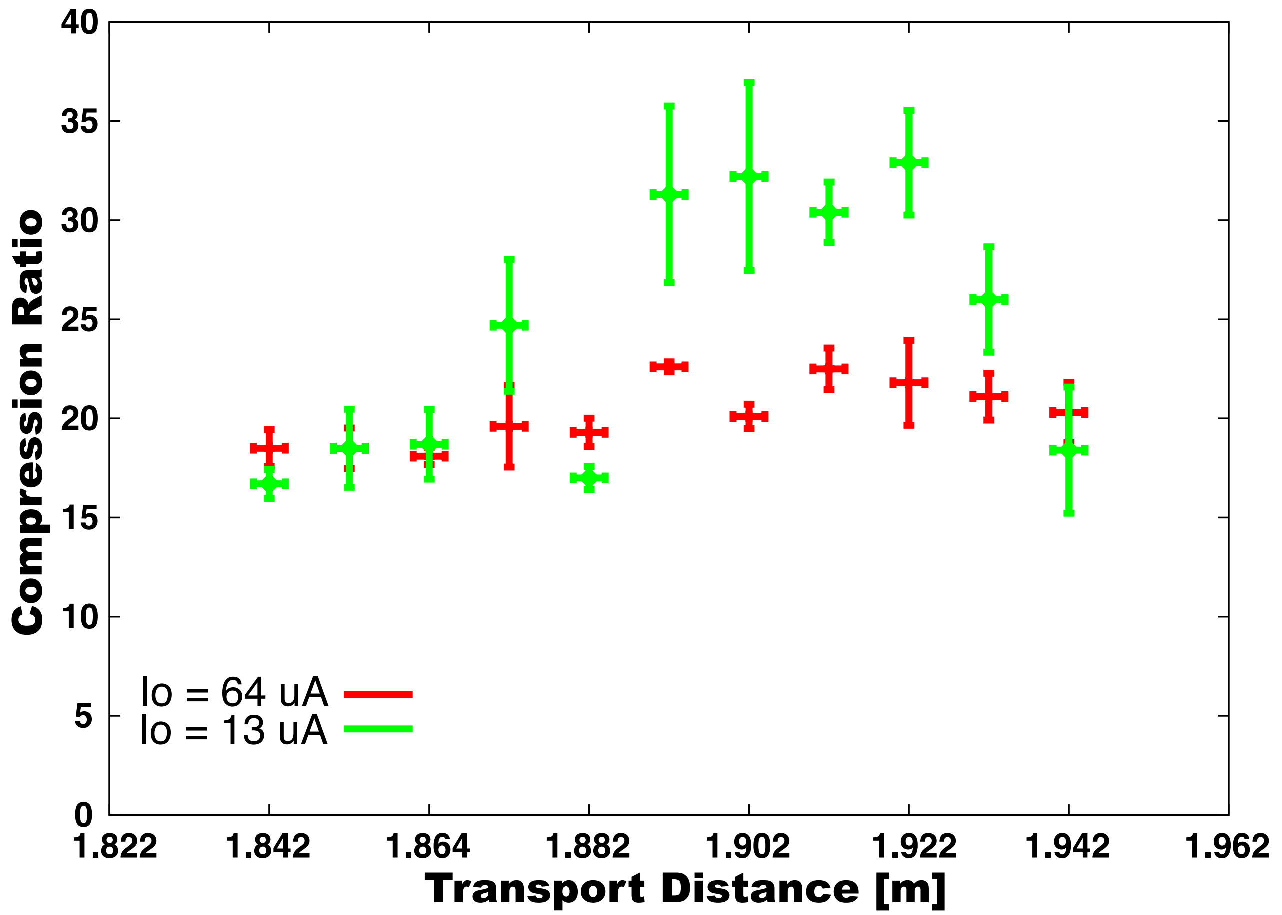
Compression Ratio as a Function of Initial Beam Current

-Compression ratio was suppressed when the initial beam current increased.



Io versus CR

Date were 8 shots averaged at fixed axial positions L=1.89 m.



L versus CR

Date were 4 shots averaged.

Conclusions

-The technology of longitudinal compression is crucial to form high-power beams.

-We made a compact simulator with electron beams to investigate the bunching dynamics.

-Results indicated that the space-charge affected the beam compression ratio.

-We are planning to discuss the collective effects on longitudinal bunch compression at higher current level.